

# REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing this collection of information. Send comments regarding this burden estimate or this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Report 4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not have a valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

Containing the  
for reducing  
A 22202-  
by a currently

0013

1. REPORT DATE (DD-MM-YYYY) 12/26/2002		2. REPORT TYPE Final		3. PERIOD OF REPORT Jan. 2000 - Jan. 2003	
4. TITLE AND SUBTITLE Studies of Transition States and Cluster-Induced Reactivity  Negative Ion Photoelectron Spectroscopy				5a. CONTRACT NUMBER F49620-00-1-0145	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Daniel M. Neumark				5d. PROJECT NUMBER 2303	
				5e. TASK NUMBER EX	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California Sponsored Projects Office 336 Sproul Hall Berkeley, CA 94720				8. PERFORMING ORGANIZATION REPORT NUMBER  011988-005	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR of Scientific Research 801 N. Randolph St., #732 Arlington, VA 22203-1977				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) F49620-00-1-0145	
12. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release/distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  Research during the last three years has focused on using negative ion photoelectron (PE) spectroscopy and zero electron kinetic energy (ZEKE) spectroscopy to probe the effects of clustering on the energetics, spectroscopy, and dynamics of ions and transition states, and to investigate the ground and excited electronic states of reactive free radicals. We have also developed a new spectroscopic method in which stimulated Raman pumping combined with PE spectroscopy is used to measure vibrational frequencies in negative ions. Results are summarized in more detail below.					
15. SUBJECT TERMS zero electron kinetic energy (ZEKE) spectroscopy					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  Unlimited (SAR)	18. NUMBER OF PAGES  8	19a. NAME OF RESPONSIBLE PERSON Daniel M. Neumark
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			19b. TELEPHONE NUMBER (include area code) 510 642-3502

20030211 130

## **FINAL TECHNICAL REPORT**

**TITLE:** Studies of Transition States and Cluster-Induced Reactivity Via Negative Ion Photoelectron Spectroscopy

**PRINCIPAL INVESTIGATOR:** Daniel M. Neumark

**DATE:** 1/15/00 – 1/14/03

**GRANT NO:** F49620-00-1-0145

**SENIOR RESEARCH PERSONNEL:** none, other than P.I.

**JUNIOR RESEARCH PERSONNEL:** Art Bragg, Alison Davis, Annelise Faulhaber, Michael Ferguson, Michael Furlanetto, Harry Gomez, Alexandra Hoops, Aster Kammrath, Beth Kautzman, matt Nee, Darcy Peterka, Nick Pivonka, Jason Robinson, Sean Sheehan Niels Sveum, Jason Gascooke, Giovanni Meloni, Andreas Osterwalder, Lionel Poisson, Zhuan Liu

**PUBLICATIONS ACKNOWLEDING THIS GRANT:** see attached

### **Abstract:**

Research during the last three years has focused on using negative ion photoelectron (PE) spectroscopy and zero electron kinetic energy (ZEKE) spectroscopy to probe the effects of clustering on the energetics, spectroscopy, and dynamics of ions and transition states, and to investigate the ground and excited electronic states of reactive free radicals. We have also developed a new spectroscopic method in which stimulated Raman pumping combined with PE spectroscopy is used to measure vibrational frequencies in negative ions. Results are summarized in more detail below.

**DISTRIBUTION STATEMENT A**  
Approved for Public Release  
Distribution Unlimited

## 1) *PE and ZEKE spectroscopy of clustered halide ions*

We have measured the ZEKE spectrum of diatomic  $\text{ArCl}^-$ , and observed transitions to the  $X1/2$  ground state and the low lying  $I3/2$  and  $II1/2$  states of neutral  $\text{ArCl}$ .<sup>1</sup> The resolution in these spectra is around  $1 \text{ cm}^{-1}$ , enabling us to resolve vibrational progressions involving the low frequency anion ( $29 \text{ cm}^{-1}$ ) and neutral ( $14\text{-}18 \text{ cm}^{-1}$ ) vibrations. Analysis of these spectra yielded the first high quality experimental potential for the negative ion, showing that the anion well depth is substantially less than that extracted from ion mobility data<sup>2</sup> (65 meV vs. 104 meV), and that the anion bond length is much longer (3.71 vs. 3.14 Å). Similar experiments<sup>3</sup> on  $\text{XeCl}^-$  also yield an accurate anion potential that is at odds with earlier ion mobility data.

The  $\text{ArCl}^-$  diatomic data was then used to analyze the ZEKE spectrum of polyatomic  $\text{Ar}_n\text{Cl}^-$  clusters ( $n=2\text{-}15$ ).<sup>4</sup> The shifts in the electron affinities (EA's) in those spectra as a function of cluster size were compared to simulated annealing calculations incorporating the diatomic anion and neutral potentials as well as non-additive terms in the anion and neutral clusters. In the absence of non-additive terms, the calculated EA's were too high by as much as  $1500 \text{ cm}^{-1}$ . The two major non-additive terms needed to yield good agreement with experiment were the expulsive many-body induction and the attractive charge-exchange quadrupole interactions, both of which occur only in the anion cluster. The EA's show a clear shell-closing at  $n=12$ , corresponding to an icosahedral arrangement of Ar atoms around the  $\text{Cl}^-$  anion.

The PE spectra of  $\text{Xe}_n\text{I}^-$  ( $n \leq 13$ ) clusters<sup>5</sup> were measured in order to resolve discrepancies in the electron affinities between an earlier, lower resolution PE study by Becker<sup>6</sup> and our previous ZEKE spectra<sup>7</sup> of these clusters. The ZEKE spectra yielded considerably lower EA's than the PE spectra by as much as 80 meV for the  $n=12$  cluster. Our new PE spectra yield EA's intermediate between the two experiments. Although the

anions are closed shell species, their spectroscopy is complicated by the existence of charge-transfer-to-solvent (CTTS) excited states that lie just below the electron detachment threshold.<sup>8</sup> These states distort the ZEKE spectra for the larger clusters, yielding artificially low apparent electron affinities that reflect the positions of the CTTS states rather than the detachment thresholds. On the other hand, the earlier PE spectra appeared to suffer from calibration errors and yielded EA's that were too high. Our spectra confirm a shell-closing at  $n=12$ , similar to that seen for  $\text{Ar}_n\text{Cl}^-$  clusters.

We also measured the anion photoelectron spectra of  $\text{I}_2^-(\text{CO}_2)_n$  clusters ( $n = 1-8$ ) at a photon energy of 4.661 eV.<sup>9</sup> The experiment yielded size-dependent vertical and adiabatic detachment energies for the formation of the ground state and low-lying valence-excited states of the neutral cluster. Vertical detachment energies were successively blue-shifted with increasing cluster size, indicating a stronger stabilization of the anionic cluster relative to the neutral counterpart. In addition, a short progression in the  $\text{CO}_2$  bending mode was observed in the  $n=1$  and 2 clusters, indicating that the  $\text{CO}_2$  solvent species are slightly bent ( $\sim 2.5^\circ$ ) in the anion clusters.

## **2) *Transition state spectroscopy in clusters***

We demonstrated several years ago that photoelectron spectroscopy of stable negative ions could be used to probe the transition state of neutral bimolecular reactions, provided that the anion and transition state geometries were similar.<sup>10</sup> Bihalide anions such as  $\text{IHI}^-$  and  $\text{BrHI}^-$  were shown to be particularly suitable transition state precursors.<sup>11-13</sup> We recently measured photoelectron spectra of  $\text{BrHI}^-(\text{Ar})$  and  $\text{IHI}^-(\text{Ar})_n$  ( $n=1-15$ ) in order to investigate the effect of stepwise solvation on transition state spectroscopy and dynamics.<sup>14,15</sup>

Our PE spectra of  $\text{BrHI}^-(\text{Ar})$  and  $\text{IHI}^-(\text{Ar})$  showed that even a single weakly bound solvent species such as Ar induced significant changes in the photoelectron spectrum of the bare anion.<sup>15</sup> These changes are primarily due to cooling effects, since a

cluster in which an Ar atom is clustered to a vibrationally excited bihalide anion will undergo predissociation before it passes through our mass spectrometer, leaving only those clusters in which the anion chromophore is vibrationally cold; similar effects have been seen in the PE spectrum of  $I_2^-(Ar)$  and in the infrared spectrum of clustered halide anions.<sup>16,17</sup> As a consequence, the vibrational features in the  $BrHI^-(Ar)$  PE spectrum are considerably narrower than in the  $BrHI^-$  spectrum,<sup>13</sup> enabling a more detailed comparison with theory. While the bare  $IHI^-$  spectrum shows a well-resolved progression in the relatively high frequency  $IHI$  antisymmetric stretch,<sup>11</sup> the  $IHI^-(Ar)$  PE spectrum shows additional structure from progressions in low frequency hindered rotor states of the  $IHI$  complex.

The PE spectra of  $IHI^-(Ar)_n$  ( $n=1-15$ ) clusters show several trends of interest.<sup>14</sup> The shifts with EA as a function of cluster size are very similar to those seen for  $I_2^-(Ar)_n$  clusters,<sup>16</sup> implying that the first six Ar atoms cluster around the waist of the  $IHI^-$ , where they can interact with the partial negative charges on the two I atoms. Subsequent Ar atoms bind primarily to a single I atom. We also observe a change in the spacing of the  $IHI$  antisymmetric stretch frequency as a function of cluster size, an effect attributed to solvent-induced distortion of the  $IHI^-$  geometry. Finally, the low-frequency hindered rotor structure seen in the binary  $IHI^-(Ar)$  cluster becomes more pronounced for the largest clusters we studied. This effect is counterintuitive, because clustering generally obscures vibrational structure in PE spectra. We attribute it to caging of the neutral  $IHI$  complex by the surrounding Ar atoms, resulting in a longer lifetime and hence sharper structure than seen in the smaller clusters. This effect, represents a remarkable demonstration of the effect of clustering on transition state dynamics.

### **3) Characterization of free radicals by anion PE spectroscopy**

Our photoelectron spectrum of  $I_3^-$  provided the first experimental observation of the  $I_3$  radical and showed it to be a bound species that is nearly linear and

centrosymmetric,<sup>18</sup> a result supported by recent electronic structure calculations.<sup>19</sup> Continuing in this vein, we have measured the photoelectron spectrum of  $\text{Cl}_3^-$  at 193 nm.<sup>20</sup> Several electronic bands are observed but no vibrational structure is resolved. Electronic structure calculations by Morukuma<sup>21</sup> indicate that while  $\text{Cl}_3^-$  is a strongly bound species with  $D_{\infty h}$  symmetry,  $\text{Cl}_3$  is at best a weakly bound, asymmetric van der Waals complex of the form  $\text{Cl}\cdots\text{Cl}_2$ . Photodetachment of  $\text{Cl}_3^-$  therefore appears to access the transition state of the  $\text{Cl} + \text{Cl}_2$  exchange reaction rather than a  $\text{Cl}_3$  minimum. The positions of the bands in the experimental PE spectrum are in reasonable agreement with electronic structure calculations.

We have also continued our investigations of the  $\text{I}_3$  radical. The electronic spectroscopy and photodissociation dynamics of the  $\text{I}_3$  radical were investigated with two experimental methods.<sup>22</sup> The ground and several low-lying excited states of  $\text{I}_3$  radical were characterized by photoelectron spectroscopy of  $\text{I}_3^-$  at 213nm. In addition, photodissociation of the  $\text{I}_3$  radical was investigated at selected photon energies by fast radical beam photofragment translational spectroscopy.<sup>23</sup> Two product channels were observed with mass ratios of 1:2 and 1:1, and translational energy ( $P(E_T)$ ) distributions were measured. The  $P(E_T)$  distributions for products with mass ratio 1:2 show that this channel corresponds to  $\text{I}_2$  plus atomic I in its  $^2\text{P}_{3/2}$  or  $^2\text{P}_{1/2}$  state. The 1:1 channel corresponds to symmetric three-body dissociation to three I atoms, a rare observation of a concerted three-body process..

The photoelectron spectrum of the  $\text{HCCO}^-$  anion was measured and analyzed by comparison with a sophisticated theoretical model that accounts for the quasi-linearity of the  $\tilde{X}^2A''$  state of  $\text{HCCO}$  and its Renner-Teller coupling to the nearby  $\tilde{A}^2A'$  state.<sup>24</sup> Because of these effects, the vibrational structure in the anion PE spectrum cannot be fit using the simple separable harmonic oscillator models that are generally used to simulate PE spectra. The spectrum could be fit reasonably well using an ab initio geometry for the

$\tilde{X}^2A''$  state that was quite close to the anion geometry, a barrier to linearity of  $643\text{ cm}^{-1}$ , and by incorporating strong coupling between the C-C and C-O stretches.

#### 4) *Vibrational spectroscopy of negative ions using stimulated Raman pumping*

We reported the first demonstration of a technique for vibrational spectroscopy of anions, stimulated Raman pumping-anion photoelectron spectroscopy.<sup>25</sup> It combines the high spectral resolution of stimulated Raman pumping with the high detection efficiency, mass-selectivity, and wide applicability of anion photoelectron spectroscopy. In this experiment, anions are vibrationally excited with stimulated Raman pumping using two pulsed lasers, a fixed frequency pump laser and tunable Stokes laser. Vibrational excitation is detected through the appearance of hot bands in the photoelectron spectrum. Hence, by integrating the hot band region of the PE spectrum while scanning the Stokes laser, we observe signal only when the difference in the pump and Stokes photon energies is equal to a vibrational transition. We obtained the vibrational spectrum of a test system,  $C_2^-$ , in which we determine the frequency of the  $1 \leftarrow 0$  vibrational transition to be  $1757.8 \pm 0.1\text{ cm}^{-1}$ , and have recently located the  $1_0^1$  transition in  $C_5^-$  at  $1853\text{ cm}^{-1}$ .

- <sup>1</sup> T. Lenzer, I. Yourshaw, M. R. Furlanetto, G. Reiser, and D. M. Neumark, J. Chem. Phys. **110**, 9578 (1999).
- <sup>2</sup> C. C. Kirkpatrick and L. Viehland, Chem. Phys. **98**, 221 (1985).
- <sup>3</sup> T. Lenzer, I. Yourshaw, M. R. Furlanetto, N. L. Pivonka, and D. M. Neumark, J. Chem. Phys. **116**, 4170 (2002).
- <sup>4</sup> T. Lenzer, I. Yourshaw, M. R. Furlanetto, N. L. Pivonka, and D. M. Neumark, J. Chem. Phys. **115**, 3578 (2001).
- <sup>5</sup> N. L. Pivonka, T. Lenzer, M. R. Furlanetto, and D. M. Neumark, Chem. Phys. Lett. **334**, 24 (2001).
- <sup>6</sup> I. Becker and O. Cheshnovsky, J. Chem. Phys. **110**, 6288 (1999).
- <sup>7</sup> T. Lenzer, M. R. Furlanetto, N. L. Pivonka, and D. M. Neumark, J. Chem. Phys. **110**, 6714 (1999).
- <sup>8</sup> I. Becker, G. Markovich, and O. Cheshnovsky, Phys. Rev. Lett. **79**, 3391 (1997).
- <sup>9</sup> H. Gomez, T. R. Taylor, and D. M. Neumark, J. Chem. Phys. **116**, 6111 (2002).
- <sup>10</sup> D. M. Neumark, Accts. Chem. Res. **26**, 33 (1993).

- 11 A. Weaver, R. B. Metz, S. E. Bradforth, and D. M. Neumark, *J. Phys. Chem.* **92**,  
5558 (1988).
- 12 I. M. Waller, T. N. Kitsopoulos, and D. M. Neumark, *J. Phys. Chem.* **94**, 2240  
(1990).
- 13 S. E. Bradforth, A. Weaver, D. W. Arnold, R. B. Metz, and D. M. Neumark, *J.*  
*Chem. Phys.* **92**, 7205 (1990).
- 14 Z. Liu, H. Gomez, and D. M. Neumark, *Faraday Disc.* **118**, 221 (2001).
- 15 Z. Liu, H. Gomez, and D. M. Neumark, *Chem. Phys. Lett.* **332**, 65 (2000).
- 16 K. R. Asmis, T. R. Taylor, C. S. Xu, and D. M. Neumark, *J. Chem. Phys.* **109**,  
4389 (1998).
- 17 C. G. Bailey, J. Kim, C. E. H. Dessent, and M. A. Johnson, *Chem. Phys. Lett.*  
**269**, 122 (1997).
- 18 T. R. Taylor, K. R. Asmis, M. T. Zanni, and D. M. Neumark, *J. Chem. Phys.* **110**,  
7607 (1999).
- 19 J. Vala, R. Kosloff, and J. N. Harvey, *J. Chem. Phys.* **114**, 7413 (2001).
- 20 A. L. Kaledin, M. C. Heaven, K. Morokuma, and D. M. Neumark, *Chem. Phys.*  
*Lett.* **306**, 48 (1999).
- 21 A. L. Kaledin, M. C. Heaven, W. G. Lawrence, Q. Cui, J. E. Stevens, and K.  
Morokuma, *J. Chem. Phys.* **108**, 2771 (1998).
- 22 H. Choi, R. T. Bise, A. A. Hoops, and D. M. Neumark, *J. Chem. Phys.* **113**, 2255  
(2000).
- 23 R. E. Continetti, D. R. Cyr, D. L. Osborn, D. J. Leahy, and D. M. Neumark, *J.*  
*Chem. Phys.* **99**, 2616 (1993).
- 24 B. Schafer-Bung, B. Engels, T. R. Taylor, D. M. Neumark, P. Botschwina, and M.  
Peric, *J. Chem. Phys.* **115**, 1777 (2001).
- 25 M. R. Furlanetto, N. L. Pivonka, T. Lenzer, and D. M. Neumark, *Chem. Phys.*  
*Lett.* **326**, 439 (2000).



## Publications:

1. M.R. Furlanetto, N. L. Pivonka, T. Lenzer, D.M. Neumark, "Vibrational Spectroscopy of Anions by Stimulated Raman Pumping-Photoelectron Spectroscopy". Chem. Phys. Lett. 326, 439, (2000).
2. Z. Liu, H. Gomez, D.M. Neumark, "Photoelectron spectroscopy of clustered transition state precursors  $\text{IHI}^-\cdot\text{Ar}$  and  $\text{BrHI}^-\cdot\text{Ar}$ ". Chem. Phys. Lett. 332, 65, (2000).
3. Z. Liu, H. Gomez, D. M. Neumark, "Transition state spectroscopy of the  $\text{I}+\text{HI}$  reaction in clusters: photoelectron spectroscopy of  $\text{IHI}^-\cdot\text{Ar}_n$  ( $n=1-15$ )" Faraday Discuss. Chem. Soc. 118, 221,(2001).
4. N. L. Pivonka, T.Lenzer, M.R. Furlanetto, D. M. Neumark, "Photoelectron Spectroscopy of  $\text{Xe}_n\text{I}^-$  Clusters ( $n \leq 13$ )". Chem. Phys. Lett. 334, 24, (2001).
5. T. Lenzer, I. Yourshaw, M. R. Furlanetto, N. L. Pivonka, D. M. Neumark, "Characterization of  $\text{Ar}_n\text{Cl}^{(-)}$  clusters ( $n=2-15$ ) using zero electron kinetic energy and partially discriminated threshold photodetachment spectroscopy" J. Chem. Phys. 115, 3578 (2001).
6. T. Lenzer, I. Yourshaw, M. R. Furlanetto, N. L. Pivonka, D. M. Neumark, "Zero electron kinetic energy spectroscopy of the  $\text{XeCl}^-$  anion" J. Chem. Phys. 116, 4170, (2002).
7. N. L. Pivonka, C.Kaposta, G. von Helden, G. Meijer, L. Wöste, D. M. Neumark, K. R. Asmis, "Gas phase infrared spectroscopy of cluster anions as a function of size: the effect of solvation on hydrogen-bonding in  $\text{Br}^-(\text{HBr})_{1,2,3}$  clusters" J. Chem.Phys. 117, 6493, (2002).
8. D. M. Neumark, "Spectroscopy of reactive potential energy surfaces" PhysChemComm 5, 76, (2002).
9. D. M. Neumark, "Transition State Spectroscopy" (Submitted to Xueming Yang, Institute of Atomic and Molecular Sciences, Academia Sinica 5/3/02)
10. N. L. Pivonka, C. Kaposta, M. Brümmer, G. von Helden, G. Meijer, L. Wöste, D. M. Neumark, K. R. Asmis, "Probing a strong hydrogen bond with ifrared spectroscopy: vibrational predissociation of  $\text{BrHBr}^-\cdot\text{Ar}$ " (Submitted to J. Chem. Phys. 10/30/02)